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Author(s): Walter E. Gilmore
Chris D. Clawson
Kimberly K. Ellis

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A Risk-Based Approach for Controlling Beryllium Exposure in a Manufacturing Environment

Walter E. Gilmore
University of California, Los Alamos National Laboratory; Los Alamos, NM

Chris D. Clawson
ARES Corporation; Albuquerque, NM

Kimberly K. Ellis
University of California, Los Alamos National Laboratory; Los Alamos, NM

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Abstract

There are many diverse uses for beryllium in both military and industrial applications. Unfortunately, there are certain worker health risks associated with the manufacture and production of beryllium products. Respiratory illnesses due to prolonged contact with beryllium particulate are of paramount concern. However, these health risks can be controlled provided that the appropriate protective measures to prevent worker exposure from beryllium are in place. But it is not always a straightforward process to identify exactly what the beryllium protective measures should be in order to realize a true risk savings. Without prudent attention to a systematic inquiry and suitable evaluative criteria, a program for controlling beryllium health risks can be lacking in completeness and overall effectiveness. One approach that took into account the necessary ingredients for risk-based determination of beryllium protective measures was developed for a beryllium operation at a Department of Energy (DOE) facility. The methodological framework that was applied at this facility, as well as a discussion of the final beryllium protective measures that were determined by this approach will be presented. Regulatory aspects for working with beryllium, as well as a risk-assessment strategy for ranking beryllium-handling activities with respect to exposure potential will also be discussed. The presentation will conclude with a synopsis of lessons-learned as gleaned from this case study, as well as providing the participants with a constructive blueprint that can be adapted to other processes involving beryllium.

Introduction

The Beryllium Technology Facility (BTF), managed by the United States Department of Energy (DOE) is used for manufacturing of products containing beryllium. The facility can process beryllium in any form to produce parts used in research and development, or used directly to make the beryllium products for end use. Typical operations that take place at the BTF include: foundries, machining, plasma spray, vapor deposition, gas atomization, hot isostatic pressing, and welding. In addition, there are a variety of maintenance and support operations that routinely take place at BTF that are associated with the ventilation system, filter change out, dust collector/cartridge filter house, cyclone separator, Inductively Coupled Argon-Atomic Emission Spectroscopy (ICP) Laboratory, glove boxes/hoods, and laundry.

The major hazard posed by the activities at the BTF is the potential exposure of workers to beryllium dust, which can lead to chronic beryllium disease (CBD) or other respiratory related illness. An irreversible, potentially fatal disease, CBD is characterized by pulmonary symptoms that include dyspnea, nonproductive cough, and detriments in lung function.

A qualitative Hazards Analysis (HA) was performed at the BTF to better understand the health threats from beryllium exposure so that that controls for protecting the workers can be systematic determined. The HA considered all aspects of facility operation at the BTF, from receipt to preparation for offsite shipment of the finished product or waste material.

Technical Approach and Results

The HA was performed in three steps:

- Identify the hazards scenarios that may be associated with various beryllium related activities at the BTF.
- Perform a hazard evaluation to establish the types of scenarios that could occur involving beryllium activities. Estimate the controlled and uncontrolled likelihood of occurrence and consequences associated with each scenario.
- Identify those preventive and mitigative controls (engineered or administrative) that contribute to a reduction in the likelihood or consequences each scenario.

A discussion of the technical approach and general results that were obtained from the HA is presented in the following sections.

Hazard Identification: The hazard identification consisted of walkthroughs of the facility, interviews with subject matter experts, review of current operating procedures and reviews of the initial safety analysis documentation. Upon completion of the walkthroughs and documentation a review all possible hazards were compiled and reviewed. Therefore, the accidents of concern are those that result in either airborne, respirable beryllium or in skin contamination, or both.

Table 1 lists the general hazards and general initiator identified for workers.

Table 1 - Potential Worker Exposures as a Result of Activities and Operations

Hazards	Results
Dispersal of Be through thermal and/or explosive insults	Fire or explosion (including those induced by spontaneous combustion, electrical malfunctions, vehicle fires, vehicle crash, seismic event, high winds, lightning, etc.)
	Exothermic chemical reaction with Be materials
	Furnace/process chamber door opened prior to adequate cool-down
Mechanical release/dispersal of Be	Spills of solutions and powders
	Drops and shipping/receiving accidents
	Mechanical impact (vehicle crash, seismic event, high winds, lightning, floods, etc.)
	Worker contamination events (general)
Failure of BTF ventilation and filtration systems	Improper ventilation flows/balance
	Loss of filter integrity, ductwork failure

Hazard Evaluation:

To Evaluate the hazards once they have been identified the team proceeded to take the following steps:

- List and describe all existing hazard controls.
- As a team, systematically review the hazards applicable to the facility, process, or activity under evaluation and construct HA tables.
- Perform "what-if" evaluations to define credible (and incredible) accident scenarios.
- Characterize each scenario in terms of the estimated likelihood and consequences of the accident. Assignments of likelihood were made based on frequency information previously collected and on the collective judgment of the team members. Potential consequences due to beryllium exposure from uncontrolled accidents were based on scoping analyses and on the collective judgment of the team members.
- For each individual accident scenario, identify and record in the tables the controls that can be applied to reduce risk. Estimate the revised accident frequency or consequences due to the application of the controls.
- Document key assumptions used in evaluating each accident scenario. Similarly, notes pertinent to the understanding of each accident scenario were documented.
- Using established risk matrices, note for each accident scenario the risk to the public and to workers, both before and after application of controls.
- Review the HA tables with BTF SMEs to check for reasonableness, comprehensiveness, and accuracy. Modify the tables as appropriate based on SME input.
- Where appropriate, recommend additional controls to enhance safety.

The hazard tables were used to qualify overall risk to the worker from each individual scenario. The risk was determined through the use of an algorithm taking both mitigated consequence and frequency into account. The tables reflected how well the controls mitigate the risk to workers. These controls are reflected in lowering both consequence and most frequencies involving these scenarios. A list of the specific fields of information that were collected for the HA tables is shown in Table 2.

Table 2 – Categories of Information Collected for the HA Tables

- Scenario Number
- System/Process
- Equipment if Applicable
- Hazard
- Accident Type (Energy Source)
- Accident Scenario
- Unmitigated Consequence (Likelihood, Worker, Public)
- Existing Controls
- Recommended Controls
- Assumptions
- Notes
- Beryllium Form
- Mitigated Consequence (Likelihood, Worker, Public)
- Unmitigated Risk (Worker, Public)
- Mitigated Risk (Worker, Public)

Likelihood, Consequence, and Risk matrices: The Likelihood, consequence and risk determination was done using team members best engineering judgment for these scenarios. These judgments were developed from documentation reviews, SME interview and applying appropriate knowledge from performing other such analysis at other facilities. The basic methodology is based on the guidance provided in the Los Alamos National Laboratory document entitled *Hazard Analysis Technical Methodology Handbook,* FWO-OAB-501.

The Likelihood table used in assessing risk to the workers is presented in Table 3.

As shown in Table 3, Both qualitative and quantitative descriptions of the frequency bins are provided. The likelihood is broken down into 5 possibilities:

- Likely to occur <u>often</u> during the life of the facility
- Likely to occur <u>several times</u> during the life of the facility
- Should not occur during the life of the facility but could
- Unlikely but possible to occur during the life of the facility
- Should not occur during the life of the facility

These five likelihoods create "bins" into which scenario possibilities are placed. These 5 categories were compared with the consequence from the accident to determine overall risk to worker.

Table 3 – Likelihood Table for BTF Hazard Analysis

Classification	Likelihood	Description	Comment
I	$> 10^0$/y	frequent (expected)	***Likely to occur often during the life of the facility*** Incidents that occur during normal operation
II	10^0/y to $< 10^{-2}$/y	probable (likely)	***Likely to occur several times during the life of the facility*** (Incidents that may occur during the lifetime of the facility; these are incidents with a mean expected likelihood of once in 50 years).
III	10^{-2}/y to $< 10^{-4}$/y	occasional (unlikely)	***Should not occur during the life of the facility, but could*** (Incidents that are not anticipated to occur during the lifetime of the facility, but could; these incidents have a likelihood of between once in 100 years to 10,000 operating years).
IV	$< 10^{-4}$/y to $>10^{-6}$/y	improbable (extremely unlikely)	***Unlikely but possible to occur during the life of the facility*** (Incidents that will probably not occur during the lifetime of the facility; these are incidents having a likelihood of between once in 10,000 years and once in a million years).
V	$< 10^{-6}$/y	remote (beyond extremely unlikely	***Should not occur during the life of the facility*** (All other incidents having a likelihood of less than once in 1,000,000 operating years)

While the general methodology of the *Hazard Analysis Technical Methodology Handbook* (FWO-OAB-501) was followed in constructing consequence matrices, some custom adaptations were deemed appropriate and necessary due to the unique, and still indeterminate, adverse health consequences associated with beryllium exposure. These custom adaptations are predominately focused on defining the consequence severity categories within a context of airborne beryllium exposure levels.

The levels selected for each category are based on existing regulatory standards and the most current technical guidelines. In certain instances, the best available information from peer-reviewed literature was also adopted to establish airborne beryllium exposure levels for those categories where regulatory standards and technical guidelines were not available. As depicted by the categories presented, the degree of severity is proportional to an airborne concentration in $\mu g/m^3$. For the purpose of making relative comparisons between categories, it was assumed that any exposures resulting from a scenario would be of an acute nature. Although it is recognized that certain airborne concentrations are time dependent, no attempt was made to factor long-term exposure durations (such as those of a chronic nature) into a severity outcome for any given scenario. Instead, category selection for each scenario was established in terms of a discernable accident or discrete event, whereby the public or worker recipient is subjected to an exposure that could be inferred as being close to instantaneous. In this manner, the categories as they appear in the consequence tables were applied to gain a first order approximation toward identifying candidate scenarios for detailed accident analysis. The Worker Consequence Table is provided in Table 4.

Table 4 – Worker Consequence Severity Category Table – Beryllium Exposure

Severity Category	
Category	**Definition**
A	High Be Dust Generation Activity Be Exposure Intensity to the worker is expected to be: $\geq$ 100 $\mu g/m^3$
B	Medium Be Dust Generation Activity Be Exposure Intensity to the worker is expected to be: $\geq$ 2.0 $\mu g/m^3$ **AND** < 100 $\mu g/m^3$
C	Low Be Dust Generation Activity Be Exposure Intensity to the worker is expected to be: $\geq$ 0.2 $\mu g/m^3$ **AND** < 2.0 $\mu g/m^3$
D	Minimal Be Dust Generation Activity Be Exposure Intensity to the worker is expected to be: $\geq$ 0.05 [4] $\mu g/m^3$ **AND** < 0.2 $\mu g/m^3$
E	No Evidence of Be Dust (Probably "Clean" or NonDetectible Amounts) Be Exposure Intensity to the worker is expected to be: < 0.05 $\mu g/m^3$

The categories for Worker Severity Consequences presented in Table 4 are defined in accordance with the postulated exposure intensity that the worker cohort would likely encounter during the performance of a particular activity. The basis for defining these categories and the assumptions for use and interpretation of Table 4 are presented in the following sections.

Consequences Table for Worker Exposure: Basis for Definition of Categories: The categories ("A" through "E") for worker consequences are based upon levels of exposure intensity. Intensity, for purposes of categorization, was generally translated to the amount of "dust" (or fines) that could be lofted into an airborne state. Initiators for dust dispersal were postulated to occur for a variety of reasons ranging from mechanical failure of process equipment to human error.

Each category for exposure intensity was roughly quantified for a given range of potential dust concentration received by the worker. Category "E" , a value of < 0.05 $\mu g/m^3$, was established as the lowest level of dust concentration. In general, any concentrations below this level would be considered as a nonberyllium operation and hence a "clean" area with respect to beryllium contamination (LIR 402-560-01).

Categories "D" and "C" were established as intermediate levels with upper range boundaries of < 0.2 $\mu g/m^3$ AND < 2.0 $\mu g/m^3$ respectively. Two $\mu g/m^3$ represents the exposure limit as adopted by the Department of Energy (DOE) for chronic beryllium disease prevention. Two-tenths $\mu g/m^3$ is an action level (or trigger level) that was also adopted by the DOE as a limit requiring the need for evaluation and corrective action in the event that this value were exceeded (10 CFR 850, DOE G 440.1-7A). Category "B" was assigned an upper range boundary of < 100 $\mu g/m^3$. One hundred $\mu g/m^3$ was identified from early investigations concerning the epidemiological basis of beryllium-related diseases (Ridenour and Preuss, 1991). It was recognized from these early investigations that chemical pneumonitis was endemic in populations who had received exposures greater than 100 $\mu g/m^3$, while no cases of this illness were reported for those who received less than this concentration. Lastly, category "A" was set as the highest level of airborne concentration, taking into account any exposure levels > 100 $\mu g/m^3$.

Consequences Table for Worker Exposure: Assumptions for Use and Interpretation: A category for worker consequences was assigned to each scenario. In order to ensure consistency in judgment, it was recognized that the category assignments should adhere to certain assumptions. The assumptions furnished guidance of a practical nature for making systematic assignments across all scenarios. In general, the assumptions furnished a framework for assessing what the properties of beryllium should be, as well as ascertaining the points of greatest exposure potential to the worker. A rationale for understanding the conditions under which an exposure pathway would propagate was also documented.

An overview of these assumptions is presented below.

Beryllium Characteristics: It has been suggested in the literature that the size of beryllium particles may be stronger determinants of adverse health outcomes by contrast to the total dispersible amount. In order to establish a degree of conservatism for the determination of consequences, it was assumed that all airborne particles would be of a respirable size. Final treatment of consequences also took into account alternative pathways of beryllium uptake in addition to those of a respiratory nature (e.g., such as beryllium exposure through an open skin wound).

Zone of Beryllium Exposures: Postulated concentrations of airborne beryllium assumed those levels that may occur in the vicinity of the worker's breathing zone[1]. This is the zone that would typically be measured by personal monitoring equipment. The presence of surface contamination in the work area was usually not considered in the worker's breathing zone, unless causal events could be identified that would convert contaminated surfaces to an airborne state. For example, surface contamination can become airborne by a cleaning activity. Solid materials were also excluded from consideration, unless airborne quantities could be produced by the activity (e.g., machining operation).

[†]Breathing Zone – A hemisphere forward of the shoulders, centered on the mouth and nose, with a radius of 6 to 9 inches.

In these instances, only the airborne proportions of the beryllium that would likely be detected by personal monitoring would be accounted for in the derivation of consequences. (Note: In allowing for conservatism, beryllium exposures were generally assessed without credit for the use of face respirators or breathing air).

Equipment Processes and Task Conditions: Although an exposure-response relationship for beryllium is not well defined, it is often purported that adverse health effects are approximately proportional to the airborne exposure concentrations experienced by the worker. This conceptual relationship is consistent with current industrial hygiene practices for beryllium management, whereby beryllium operations adhere to a philosophy of "as low as reasonably achievable." That is, keeping beryllium levels to a minimum is consistent with a commensurate reduction in cases due to beryllium-related disease. Therefore, it was logical to assume that consequence determinations would be linked to the equipment processes and task conditions that a worker might encounter during a given event. In effect, each process or task was relatively ranked according to the amount of beryllium dust likely to be produced by the operation. To illustrate, low dust generation was likely to be observed when the activity required nondestructive examination or simple visual inspection on a finished beryllium article. Moderate dust generation may be encountered while maintaining process equipment within the confines of a beryllium area. High dust generation may be associated with operations involving a filter change-out. Regardless of the determination made, consequences resulted from the known features of a process, as well as from the duties that the worker would be performing in proximity to the process.

The combinations of likelihood and consequence levels results in various risk levels. The worker hazard risk matrix is presented in Table 5.

Table 5 – Worker Hazard Risk Matrix

SEVERITY	LIKELIHOOD: I	II	III	IV	V
A	1	1	1	2	3
B	1	1	2	3	4
C	1	2	3	4	4
D	2	3	4	4	4
E	4	4	4	4	4

The risk levels were used to assess the potential at which workers will develop CBD or other respiratory-related illness from beryllium exposure (e.g., "1" – highest risk, "4" – lowest risk).

Results of the Hazard Evaluation: A summary of accidents with the potential to injure workers to hazardous levels of airborne beryllium dust includes the following:

- Fires (internal and external)
- Explosions
- Natural phenomena that result in damage to BTF building structures and/or beryllium equipment
- Mechanical insults and spills
- Failures of ventilation and filtration systems
- Miscellaneous contamination scenarios associated with erroneous worker actions

Results of the HA indicated that several of operations are highly energetic and done under high temperatures and/or pressures.
These operations could directly lead to accidents through failures of equipment or personnel or could cause an accident through secondary interactions such as fire in building during operations that leads to failure of equipment. Overall, high energy systems tend to result is highest risk during accidents, this is common sense, but is proven through analysis.

Upon completion of the hazard analysis a pattern developed throughout the document. Scenarios involving seismic anomalies, explosions and large-scale fires, related to the scenarios that generated the highest risk. The final set of controls developed in the HA were made to help mitigate these issues and reduce there overall occurrence and severity if possible. A comparison showing the original unmitigated risk (uncontrolled – no credit for controls) versus mitigated risk (controlled – credit for controls) for all scenarios analyzed is shown in Figure 1.

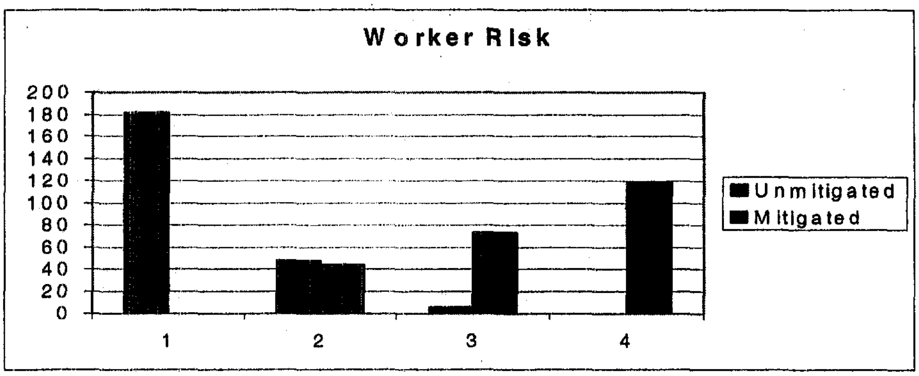

Figure 1 – Worker risk

<u>Identification of Controls:</u>

The use of controls is to help mitigate the accident either by reducing likelihood or reducing consequence or both. There are two types of controls identified in the process, administrative and engineered controls. Administrative controls are those controls which are done administratively through such things as training, documented good practices, regulations, or requirements set my management. Engineered controls are controls designed to physically stop operations, prevent operations, warn other remotely or automatically or some equivalent means of backing up operators when error are made in operations.

There are two levels to the controls detailed above, that is defense in depth, and safety related controls. Defense in depth controls are controls that will help minimized likelihood or consequence a small amount, but are not critical for operations. The process used in the HA to identify the controls is shown below:

- review all accident scenarios and select those with a high (designation "A") uncontrolled consequence to either workers or the public.
- based on information in HA tables and knowledge of the hazards and accidents, identify engineered and administrative controls that have the potential to reduce the accident consequences or frequencies for each of the accident scenarios with significant consequences.
- select those controls that have a significant potential to reduce the accident consequences by one category or more, i.e., from "A" to "B". Where the benefit for frequency, consequence, or risk reduction cannot be assigned to individual engineering or administrative controls, identify control groups that are believed to accomplish the safety benefit, therefore, in some cases, control groups were selected rather than individual controls; in all cases, the selection of important controls was based on engineering judgment (using knowledge of the hazards, accidents, and limitations of what an individual control or control group can accomplish) as "effectiveness factors" were not established or assigned in the initial HA table development.
- engineered controls are generally to be preferred over administrative controls.
- for the engineered controls identify those whose failure could result in the most adverse conditions (i.e., most extensive release of beryllium). If controls in a set cannot be ranked on this basis, rank equally effective controls on the basis of practicality.

The safety related controls provide a great amount of protect, but all controls developed help improve overall safety for operations at the facility. An overview of the general controls that were identified by the HA is shown in Table 7.

Table 7 – General Controls

Be Protection (Includes CBDPP and Ventilation System)
Be Material at Risk (MAR) Control Program
Fire Protection Program
Preventive Maintenance Program
Configuration Management Program
Procedures/HCPs
Training Program

Discussion and Conclusion

The Hazard Analysis has been demonstrated as a useful tool for systematically identifying the hazards associated with beryllium operations, and providing means for controlling them. Two important controls were defined as being needed to help improve overall facility safety. The first was adding a seismically improved safe to facility to allow for a greater amount of beryllium to be stored in the facility. The other was to enclose the ventilation discharge area in a seismically certified building. The rest of the facility meets seismic qualifications, but the main part of the ventilation system was left unprotected from traffic and other such hazards. These hazards were identified initially and reinforced through accident analysis as being important, and the seismically qualified building for the ventilation is safety related.

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Biographies

Walter E. Gilmore, Technical Staff Member, University of California, Los Alamos National Laboratory, Probabilistic Risk Analysis Group, MS K557, P. O. Box 1663, Los Alamos, NM 87545, Phone: (505) 667-2461, fax: (505) 667-5531, wgilmore@lanl.gov

Chris D. Clawson, Senior Safety Analyst, ARES Corporation, 851 University Blvd. SE Suite 100, Albuquerque, NM 87106, Phone: (505) 272-7102, fax: (505) 272-7238, Cclawson@arescorporation.com

Kimberly K. Ellis, Technical Staff Member, University of California, Los Alamos National Laboratory, Materials Science and Technology Operations Group, G741, P. O. Box 1663, Los Alamos, NM 87545, Phone: (505) 665-8215, fax: (505) 665-9136, ellisk@lanl.gov